

# Evolution and Explosion of Very Massive Primordial Stars

Alexander Heger<sup>1</sup>, S. E. Woosley<sup>1</sup>, Isabelle Baraffe<sup>2</sup>, and Tom Abel<sup>3</sup>

<sup>1</sup> Department of Astronomy and Astrophysics, University of California, 1156 High Street, Santa Cruz, CA 95064, U.S.A.

<sup>2</sup> Ecole Normale Supérieure, C.R.A.L (UMR 5574 CNRS), 69364 Lyon Cedex 07, France

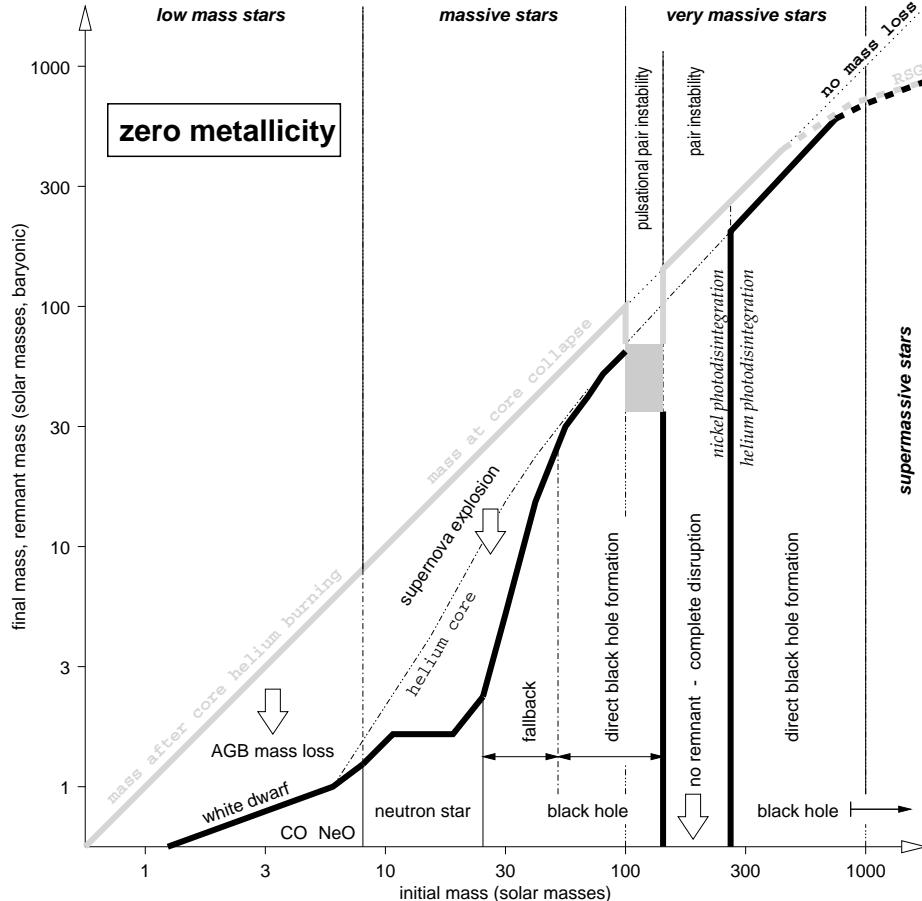
<sup>3</sup> Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, England

**Abstract.** While the modern stellar IMF shows a rapid decline with increasing mass, theoretical investigations suggest that very massive stars ( $\gtrsim 100 M_{\odot}$ ) may have been abundant in the early universe. Other calculations also indicate that, lacking metals, these same stars reach their late evolutionary stages without appreciable mass loss. After central helium burning, they encounter the electron-positron pair instability, collapse, and burn oxygen and silicon explosively. If sufficient energy is released by the burning, these stars explode as brilliant supernovae with energies up to 100 times that of an ordinary core collapse supernova. They also eject up to  $50 M_{\odot}$  of radioactive  $^{56}\text{Ni}$ . Stars less massive than  $140 M_{\odot}$  or more massive than  $260 M_{\odot}$  should collapse into black holes instead of exploding, thus bounding the pair-creation supernovae with regions of stellar mass that are nucleosynthetically sterile. Pair-instability supernovae might be detectable in the near infrared out to redshifts of 20 or more and their ashes should leave a distinctive nucleosynthetic pattern.

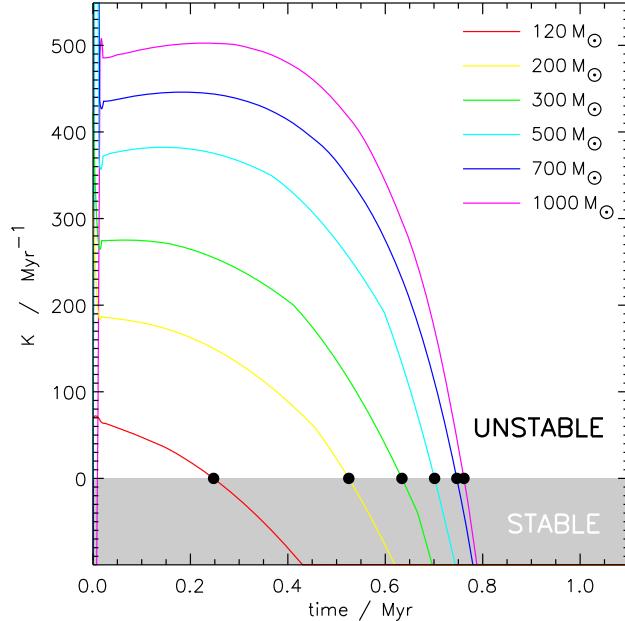
## 1 Introduction

Owing to the lack of any metals, the cooling processes that govern star formation are greatly reduced for first generation of stars (Pop III). Magnetic fields and turbulence may also be less important at these early times [1]. Consequently, theoretical studies [11] indicate that the Jeans mass for primordial stars in their special environment may have been as great as  $\sim 1000 M_{\odot}$ . Numerical simulation of primordial star formation predict the occurrence of such stars at red shifts  $\sim 20$  and an initial mass function (IMF) that either peaks at  $\sim 100 M_{\odot}$  [1,4] or is bimodal [12], i.e., also contains stars of a few  $M_{\odot}$ .

Once formed, at solar metallicity, massive stars ordinarily experience significant mass loss [5] and may end as relatively small objects, but for low metallicity mass loss is suppressed. In § 2 we discuss the peculiarities of mass loss and evolution of very massive primordial stars. Figure 1 gives an overview of expected final fates of metal-free stars as a function of initial mass. In § 3 we examine the expected light curve of a pair-creation supernova from a  $250 M_{\odot}$  star at a redshift of  $z = 20$  and in § 4 we review nucleosynthetic yields from Pop III. Some conclusions are given in § 5.



**Fig. 1.** Initial-final mass function of non-rotating Pop III stars. The x-axis gives the initial mass. The y-axis gives both the final mass of the collapsed remnant (thick black curve) and the mass of the star when the event begins that produces that remnant (e.g., mass loss in AGB stars, supernova explosion for those stars that make a neutron star, etc.; thick gray curve). We distinguish four regimes of initial mass: *low mass stars* below  $\sim 10 M_{\odot}$  that end as white dwarfs; *massive stars* between  $\sim 10 M_{\odot}$  and  $\sim 100 M_{\odot}$  that form an iron core that eventually collapses; *very massive stars* between  $\sim 100 M_{\odot}$  and  $\sim 1000 M_{\odot}$  that encounter the pair instability; and *supermassive stars* (arbitrarily) above  $\sim 1000 M_{\odot}$ . Since no mass loss is expected for  $Z = 0$  stars before the final stage, the grey curve is approximately the same as the line of no mass loss (dotted). Exceptions are  $\sim 100 - 140 M_{\odot}$  where the pulsational pair instability ejects the outer layers of the star before it collapses, and above  $\sim 500 M_{\odot}$  where pulsational instabilities in red supergiants may lead to significant mass loss [2]. Since the magnitude of the latter is uncertain, lines are drawn dashed. For a more detailed description, please refer to [7]



**Fig. 2.** Growth rate,  $K$ , as a function of the age of the star. The amplitude of the pulsation grows with time as  $A(t) = A_0 \exp\left\{\frac{2\pi i}{P}t\right\} \exp\{Kt\}$  [2].

## 2 Mass Loss

Current studies of winds driven from hot stars by interactions with atomic lines indicate that their mass loss rate decreases with metallicity as  $Z^{1/2}$  [8,9] or even more [16]. This scaling seems to hold down to 0.1 % solar metallicity. Extrapolating to zero, it seems reasonable that mass loss from this wind driving mechanism becomes negligible. Winds driven by continuum opacity in low metal stars are not very well understood (Kudritzki, priv. com.), and will be neglected here.

Stars above  $\sim 60 M_{\odot}$  may also be unstable to the epsilon mechanism - pulsations driven by the high temperature sensitivity of nuclear burning [10,13]. However, historical studies of stellar stability focused on stars of solar composition and did not take into account the peculiarities of the first generation of stars. We have recently studied the pulsational instability due to epsilon mechanism in massive metal-free stars between 120 and  $1000 M_{\odot}$  [2]. Their structure is uniquely different from later stellar generations. Since hydrogen burning through the “pp-chain” is not sufficient, the star contracts to a high enough temperature to produce carbon by the triple-alpha reaction, more than  $1 \times 10^8$  K in the stars investigated here. A mass fraction of  $\sim 1 \times 10^{-9}$  is sufficient to stop the contraction and supply energy by the CNO cycle for hydrogen burning. The stars, however, stay very compact and hot in their centers throughout their hydrogen burning lifetime. The higher temperature causes a lower temperature sensitivity of the nuclear energy generation. From pulsational analysis we find that the ep-

silon mechanism is weak in these compact stars and operates only for a fraction of the hydrogen-burning life-time (Fig. 2) [2]. Radial pulsations driven by opacity or recombination are not found. We estimate that the resulting mass loss due to the epsilon mechanism should be less than 5 % for a  $500 M_{\odot}$  star, and perhaps 10 % for a  $1000 M_{\odot}$  star, but quite negligible for stars of lower mass. Stars of  $\sim 500 M_{\odot}$  or more may encounter a red supergiant phase towards the end of central helium burning. This could result in an additional, maybe significant, mass loss, but its strength is not yet known. Therefore stars of  $\lesssim 500 M_{\odot}$  can be safely assumed to reach carbon burning without significant mass loss.

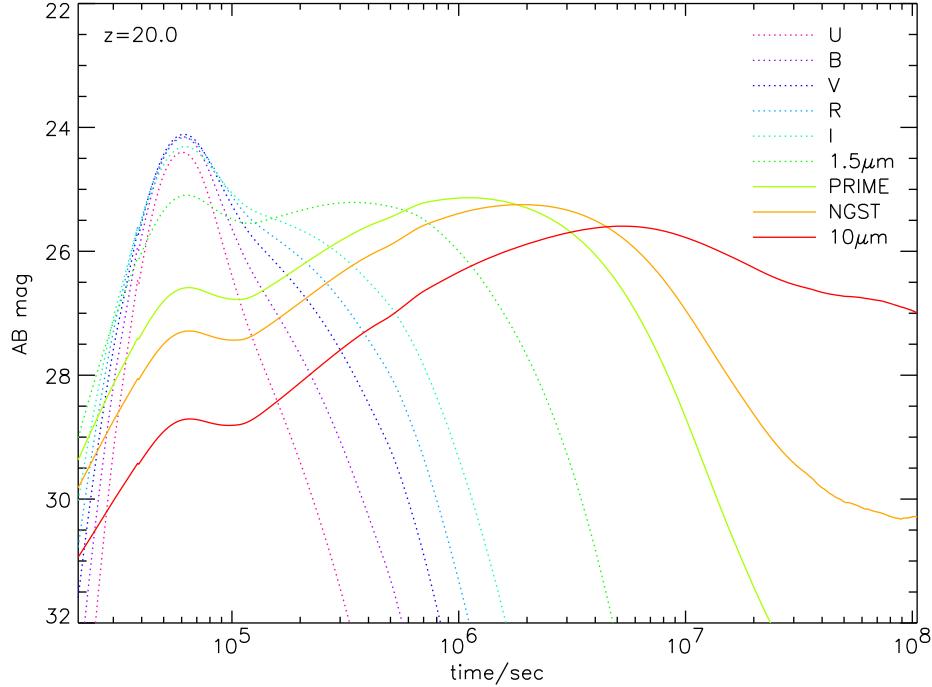
### 3 Supernovae at the Edge of the Universe

Stars that reach carbon burning with a helium core mass of  $\sim 64 \dots 133 M_{\odot}$  (corresponding to ZAMS masses of  $\sim 140 \dots 260 M_{\odot}$  for stars without mass loss) are unstable to pair-creation (see Fig. 1), collapse, then explode as a supernova (SN). These are the most powerful thermonuclear explosions in the universe. Pair-creation SNe release energies ranging from  $3 \times 10^{51}$  erg for a  $64 M_{\odot}$  He core up to almost  $100 \times 10^{51}$  erg for a  $133 M_{\odot}$  He core [7] – enough energy to disrupt a small proto-galaxy. In Fig. 3 we show, in the observer frame, the early light curve of an exploding  $250 M_{\odot}$  star, neglecting intergalactic and interstellar absorption. This star has a He core of  $120 M_{\odot}$  and a total explosion energy of  $65 \times 10^{51}$  erg, producing  $21 M_{\odot}$  of  $^{56}\text{Ni}$ . The visible brightness is not quite as impressive since most of the energy is kinetic, but nevertheless should be a few times brighter than a typical Type Ia SN. The bolometric luminosity of an event at  $z = 20$  is not much dimmer than at a red shift of a few, where Type Ia SNe have already been observed. The main difference, however, is the significantly larger red shift and time dilation. Given the bigger intrinsic time scale associated with the large ejected mass, they also last much longer.

For a current standard cosmology ( $\Omega_A = 0.7$ ,  $\Omega_m = 0.3$ ,  $H_0 = 65 \text{ km/s/Mpc}$ ,  $\Omega_b = 0.02/h^2 = 0.047$ ) and assuming that  $f_{1st} = 10^{-6}$  of all baryons goes into stars of  $M_{1st} = 250 M_{\odot}$ , at a red shift of  $z = 20$ , we estimate the pair-creation supernova rate by

$$r_{2\text{SN}} = 4\pi \left( \frac{d_{\text{lum}}}{1+z} \right)^2 \frac{c}{1+z} \rho_c \Omega_b (1+z)^3 \frac{f_{1st}}{M_{1st}} = \frac{4\pi d_{\text{lum}}^2 c \rho_c \Omega_b f_{1st}}{M_{1st}}$$

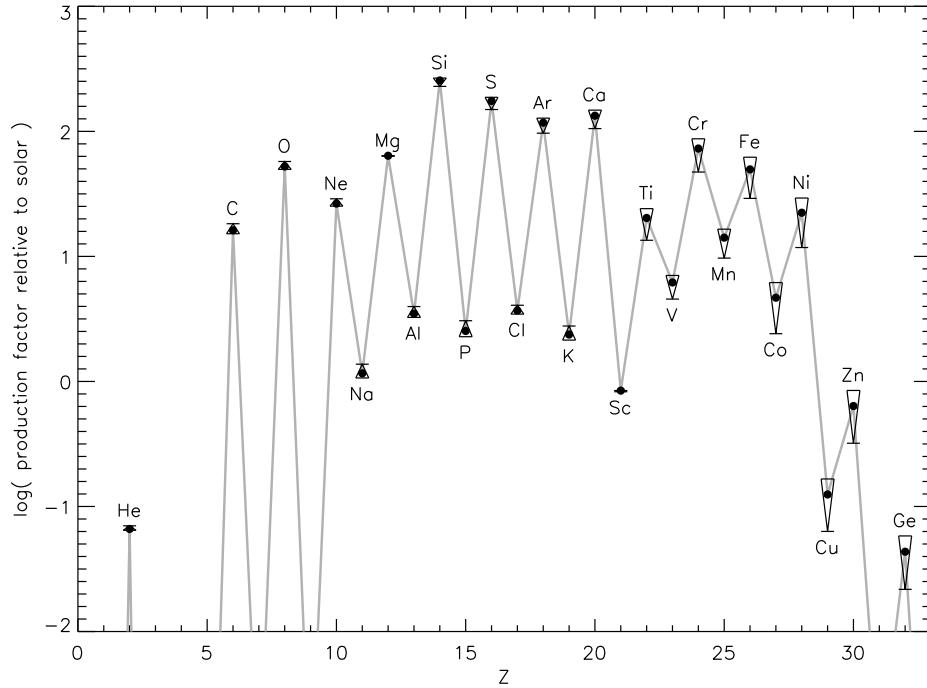
where  $\rho_c = 3H_0^2/8\pi G$ , and the luminosity distance  $d_{\text{lum}} = 243 \text{ Gpc}$ . This gives  $\sim 0.16$  events per second per universe, i.e.,  $\sim 3.9 \times 10^{-6}$  events per second per square degree. The first peak of the light curve (Fig. 3) lasts for about a month, the second peak (“plateau”; not depicted here), probably brighter in the far infrared, would peak for about 10 yr (based on preliminary calculations by Phil Pinto, priv. com.). Statistically, at any time per square degree about a dozen of these supernovae should be at the peak of the light curve, and more than  $\sim 1000$  in the plateau phase of the light curve. Note that  $d_{\text{lum}} \propto z$  for high  $z$  and thus this rate depends critically on the red shift adopted as well as on the baryon fraction assumed to go into these stars.



**Fig. 3.** Preliminary light curve of pair-creation supernova from a  $250 M_{\odot}$  star at  $z = 20$  as computed by the KEPLER code [17]. Time, wave lengths and magnitudes (without internal or intergalactic extinction) are given in observer rest frame. Wave lengths that are beyond the IGM Ly- $\alpha$  absorption ( $2.55 \mu\text{m}$ ) are displayed as dotted lines. “PRIME” and “NGST” corresponds to  $3.5$  and  $5.0 \mu\text{m}$ . The “spherically symmetric” emission has been folded to account for the extent of the “photosphere”. The first “bump” at  $\sim 10^3$  s is from the shock breakout, the right “peak” is the peak of the SN light curve.

#### 4 Nucleosynthesis

In massive stars most of neutrons responsible for the “weak component” of the  $s$ -process are made from initial CNO seeds during helium burning. Since Pop III stars are devoid of these seeds, both the  $s$ -process and the production of a “neutron excess” for the advanced burning stages is strongly suppressed [14]. In massive stars the odd- $Z$  elements are therefore underproduced with respect to the  $\alpha$  elements [7]. Above  $\sim 25 M_{\odot}$  significant fallback onto the remnant already occurs after the SN [6] (Fig. 1), and few or no heavy elements can be ejected. From  $\sim 40$  to  $\sim 100 M_{\odot}$  a black hole is formed directly [6] and essentially the whole star will be swallowed — no nucleosynthesis products are ejected. Between  $\sim 100$  and  $\sim 140 M_{\odot}$  the pulses of pair instability [3] will eject the outer layers of the star, possibly including parts of the CO core, especially at the high-mass end of the regime, but nothing heavier than magnesium leaves the star. After the pulses these objects probably encounter the same fate as their lighter cousins, i.e., the remaining part of the star falls into a black hole.



**Fig. 4.** Elemental production factors relative to solar in Pop III pair-creation supernovae (helium core mass  $65\text{--}130 M_{\odot}$ ). The thin and thick ends of the triangle and the dots correspond to IMF slopes of  $d \log N / d \log M = -1.5$ ,  $-4.5$ , and  $-2.5$ , respectively.

For initial masses of  $\sim 140 \dots 260 M_{\odot}$ , the pair instability completely disrupts the star when explosive burning of oxygen and silicon release enough energy to reverse the collapse into an explosion. However, this explosion is too rapid and the star not dense enough at the point when the implosion turns around to lead to significant neutronization. A very marked odd-even pattern results (Fig. 4) with silicon being the biggest overproduction and elements above germanium are essentially not produced. In stars more massive than  $\sim 260 M_{\odot}$ , photo-disintegration of nuclei becomes important and the collapse is not reversed. The whole star falls into a black hole (Fig. 1).

## 5 Conclusions

Due to the absence of metals the first generation of star will likely not experience significant mass loss by radiation-driven stellar winds or opacity-driven pulsations. Their unique structure also prevents significant mass loss by the epsilon mechanism. Therefore very massive Pop III single stars reach carbon burning with enough mass to encounter the pair instability. Since current theoretical studies indicate that such star may constitute a significant, if not dominant, fraction of Pop III, we predict that their nucleosynthetic yields may have a

unique imprint on the chemical evolution of the early universe. Their production of odd- $Z$  elements is by  $\sim 2$  orders of magnitude lower than that of even- $Z$ . Elements heavier than zinc are not produced.

Since stars of lower mass ( $\lesssim 140 M_{\odot}$ ) or higher mass ( $\gtrsim 260 M_{\odot}$ ) collapse into black holes without significant heavy element creation. Pair-creation SNe are thus a “clean” source of nucleosynthesis in the sense that neighboring mass ranges do not “pollute” the sample. In case of a bimodal Pop III IMF, massive stars in the range  $\sim 8 \dots 40 M_{\odot}$  will also contribute to the resulting abundance pattern, though on a slightly slower time-scale (factor  $\sim 2$ ). Also in them, the lack of initial CNO “seeds” will lead to an elemental odd-even pattern, though much less expressed [7], and they possibly contribute  $r$ -process isotopes. It is even conceivable that Pop III AGB stars contribute some  $s$ -process [15]. The interaction of the ejecta with the surrounding matter, a possible enrichment of the intergalactic medium and mixing of contributions from different-mass sources before the formation of the first Pop II stars will have to be studied in more detail in the future.

We predict that Pop III pair-creation SNe might be detectable by future near infrared space experiments — all the way out to the edge of universe — to redshifts of 20 or more. Combined with the challenge to find old Pop II stars that show the predicted abundance pattern from the ashes of these explosions, this should allow deeper insight into the happenings at the times when the first sparks of stellar light terminated the “dark ages”.

**Acknowledgments** This research has been supported by the NSF (AST 97-316569), the DOE ASCI Program (B347885), the DOE SciDAC Program, and the Alexander von Humboldt-Stiftung (FLF-1065004).

## References

1. T. Abel, G. L. Bryan, M. L. Norman: Science (2001)
2. I. Baraffe, A. Heger, S. E. Woosley: ApJ **550**, 890 (2001)
3. J. R. Bond, W. D. Arnett, B. J. Carr: ApJ **280**, 825 (1984)
4. V. Bromm, P. S. Coppi, R. B. Larson: ApJL **527**, L5 (1999)
5. D. F. Figer, F. Najarro, M. Morris, I. S. McLean, T. R. Geballe, A. M. Ghez, N. Langer: ApJ **506**, 384 (1998)
6. C. L. Fryer: ApJ **522**, 413 (1999).
7. A. Heger, S. E. Woosley: ApJ, accepted; astro-ph/0107037 (2001)
8. R.-P. Kudritzki: ‘Wind Models and Ionizing Fluxes of Massive Stars’. In: *The First Stars*, ed. by A. Weiss, T. Abel, V. Hill (Springer, Berlin 2000).
9. R.-P. Kudritzki, J. Puls: ARA&A **38**, 613 (2000)
10. P. Ledoux: ApJ, **94**, 537 (1941)
11. R. B. Larson: MNRAS **301**, 569 (1998)
12. F. Nakamura, M. Umemura: ApJ **548**, 19 (2000)
13. M. Schwarzschild, R. Härm: ApJ **129**, 637 (1959)
14. Truran, J. W., & Arnett, W. D. 1971, Ap&SS, **11**, 430
15. P. Ventura, F. D’Antona, I. Mazzitelli, R. Gratton: ApJ, **550**, L65 (2001)
16. J. S. Vink, A. de Koter, H. J. G. L. M. Lamers: A&A **369**, 574 (2001)
17. T. A. Weaver, G. B. Zimmerman, S. E. Woosley: ApJ **225**, 1021 (1978)
18. S. E. Woosley, A. Heger, T. A. Weaver: Rev. Mod. Phys., accepted (2002)